Experimental Free-Space Distribution of Entangled Photon Pairs over a Noisy Ground Atmosphere of 13km

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We report free-space distribution of entangled photon pairs over a noisy ground atmosphere of 13km. It is shown that the desired entanglement can still survive after the two entangled photons have passed through the noisy ground atmosphere. This is confirmed by observing a space-like separated violation of Bell inequality of 2.45 ± 0.09. On this basis, we exploit the distributed entangled photon source to demonstrate the BB84 quantum cryptography scheme. The distribution distance of entangled photon pairs achieved in the experiment is for the first time well beyond the effective thickness of the aerosphere, hence presenting a significant step towards satellite-based global quantum communication.

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In the future large scale realization of quantum communication schemes [1, 2, 3], we have to solve the problems caused by the photon loss and decoherence in the transmission channel. For example, because of the photon loss and the unavoidable dark count of the current available single-photon detectorsthe maximum distance in the fibre-based quantum cryptography is limited to the order of 100km [4]. The quantum repeater scheme that combines entanglement swapping, entanglement purification andquantum memory [5, 6, 7] proposed an efficient way to generate highly entangled states between distant locations, hence providing an elegant solution to the photon loss and decoherence problem. In recent years, significant progress has been achieved in the experimental demonstration of entanglement swapping, entanglement purification and quantum memory [8, 9, 10, 11, 12], yet one still has long way to go before the above techniques can be finally integrated into a single unit in order to be useful for realistic quantum communication over large distances.

Another promising way out to realize long-distance quantum communication is to exploit satellite-based free-space distribution of single photons or entangled photon pairs [13]. In the scheme, the photonic quantum states are first sent through the aerosphere, then reflected from one satellite to another and finally sent back to the earth. Since the effective thickness of the aerosphere is on the order of 5-10km (i.e. the whole aerosphere is equivalent to 5-10km ground atmosphere) and in the outer space the photon loss and decoherence is negligible, with the help of satellites one can achieve global free-space quantum communication as long as the quantum states can still survive after penetrating the aerosphere [13].

Along this line, important experimental progress has been made very recently in the free-space distribution of attenuated laser pulses and entangled photon pairs [14, 15]. However, on the one hand, in the quantum cryptography experiment with attenuated laser pulses [14] the huge photon loss in the transmission channel leaves an eavesdropping loophole. This is because the eavesdropper could in principle exploit a transmission channel with less or without photon loss and only allow those attenuated laser pulses containing two or more photons to reach the receiver. In this way, the eavesdropper can use a beamsplitter to steal at least one photon from these specific attenuated laser pulses without being detected. On the other hand, while the achieved distance in the previous entanglement distribution experiment [15] is only on the order of 600m which is far below the effective thickness of the aerosphere, the achieved low transmission efficiency ($\sim 10^{-3}$) would not enable a sufficient link efficiency over large distances, which is, however, required for satellite-based free-space quantum communication [13].

In this letter, with the help of laser-pulse-assisted synchronization method and own designed telescope systems we drive the free-space technology further by reporting free-space distribution of entangled photon pairs over a noisy ground atmosphere of 13km. We confirm that the desired entanglement can still survive after the two entangled photons have passed through the noisy ground atmosphere with a distance beyond the effective thickness of the aerosphere. In addition, we also exploit the distributed entangled photon source to experimentally demonstrate the BB84 quantum cryptography scheme [1] without the eavesdropping loophole. The distribution distance of entangled photon pairs achieved in our experiment is for the first time well beyond the effective thickness of the aerosphere, hence presenting a significant step towards satellite-based global quantum communication.

In the experiment, as shown in Fig.1, a Sender is lo-

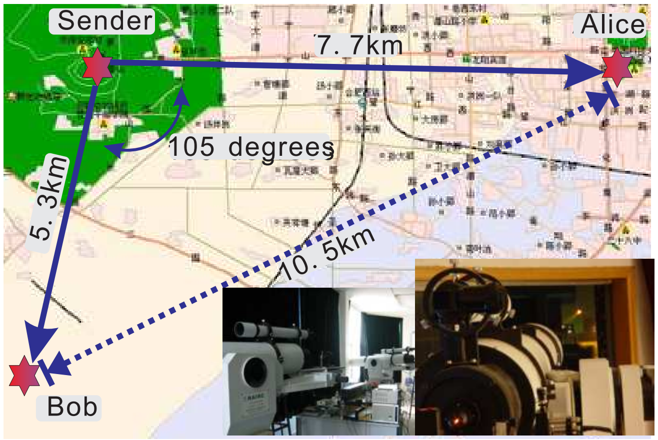

FIG. 1: Schematic diagram of locations in our experiment. The source of entangled photons is located at the foot of a high television tower, on the top of Dashu Mountain. Alice is located on the west campus of USTC, and Bob is located at Feixi, a county of Hefei city. Photons from the Sender to the receivers experience noisy city environment. Therefore, strongly influenced by the air pollution and noisy background lights, even after rain with less air pollution, the background count rate can reach about 30,000 per second at night without using interference filters.

cated on the top of Dashu Mountain in Hefei of China, with an elevation of 281m, and two receivers (Alice and Bob) are located at the west campus of USTC and at Feixi of Hefei respectively. The direct distance between the two receivers is about 10.5km. The distances from the Sender to Alice and from the Sender to Bob are, 7.7km and 5.3km, respectively. One of the two entangled photons passes through nearly half part of Hefei city, experiencing an extremely challenging environment above the city. The two receivers are not in sight with each other due to the existence of many buildings between them.

At the Sender, we utilize type-II parametric down-conversion to generate entangled photon pairs [16]. The Argon Ion laser used to pump BBO crystal has a wavelength of 351nm. When the pump power is about 300mw, with narrow bandwidth filters of 2.8nm in front of single-photon detectors we locally collect about 10,000 pairs of entangled photons per second, with an average single photon count rate about 155,000 per second.

In order to optimize the transmission efficiency and its stability, we have designed two sets of transmission system ourselves, which contain 4 large telescopes of refraction type. Each telescope weighs about 800kg, with a focus length about 2m. Lenses used in the telescope are coated to maximize the peak transmission rate at the wavelength of entangled photons (702nm). Each transmission system composed of two telescopes can achieve a transmission rate of above 70%. The wild environment on the top of Dashu Mountain brings us many difficulties, and we have taken several measures to overcome them. The two telescopes at the sender are specially designed to be robust against the strong wind.

The entangled photons at the Sender are collected into two single-mode fibers, which are connected to the two sending telescopes respectively. Due to the disturbance of the atmosphere, the size and position of the received beam vary randomly, causing reduction of the collecting efficiency. To solve this problem, we have used the two sending telescopes to expand the beam diameter to about 12cm for long-distance propagation. Moreover, at each receiver a similar telescope is used to receive the entangled photons. After being focused, entangled photons are coupled into 62.5um multi-mode fibers and finally sent to single photon detectors. With these efforts, we manage to keep the transmission system to work stably for a couple of hours. For example, in the right photography of Fig.1 we can see at the Alice side a bright and stable adjusting laser beam from the Sender.

Since the distances from Sender to Alice and to Bob are not equal, the two entangled photons will arrive at each receiver at a different time. The air disturbance will cause this time difference varying randomly, result in a time difference shake (ΔT). To coincide the detected events at the two receivers, we have to make sure that the coincident time window should be wider than (ΔT). However, when we widen the coincident time window to get the adequate true coincident events, the accidental coincident count rate also increases and thus results in a reduction of the visibility. In our experiment, we utilized the method of laser pulse synchronization to achieve time coincidence between the two receivers (See Fig.2). At the Sender, Q-switched laser pulses with a wavelength of 532nm are separated into two parts, and then sent to the receivers, experiencing the same optical path as the entangled photons. At each receiver, we measure the time difference between the signal of single-photon event and the signal of the corresponding synchronous laser pulse for subsequent coincidence via classical communication link. Consider other ingredients causing time shake, we set the time window to 20ns in our experiment.

Finally, to minimize background count rate, 2.8nm interference filters are utilized at each receiver to block the noisy background light. With the filters added, the average background count rate is about 400 per second. When the weather condition is perfect with a considerable high vis. (> 15km), total single photon count rate is about 40,000 per second at Bob, about 18,000 per second at Alice, and the coincident count rate is about 300 per second. At the normal vis. (10km), the coincident count rate is about 150 per second.

The entangled state prepared at the Sender can be expressed as follows,

$$|\psi^-\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B) \tag{1}$$

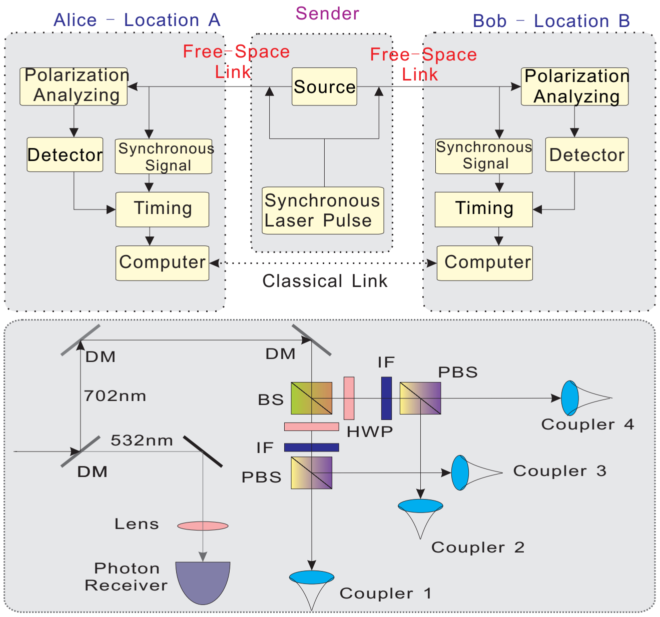

FIG. 2: Block diagram of the experiment and optical setup at the receivers. As shown in the left Figure, we combine the entangled photons with the synchronous pulsed laser beam utilizing a dichroic mirror (DM) at the Sender and separate them at each receiver with a DM. Then it follows with single photon polarization analysis and time synchronization. In the down figure, a beam splitter (BS) is used to achieve random basis selection, and a half-wave plate (HWP) together with a polarization beam splitter (PBS) make up an apparatus for polarization measurement. Interference filters (IF) are used to get rid of noisy background light.

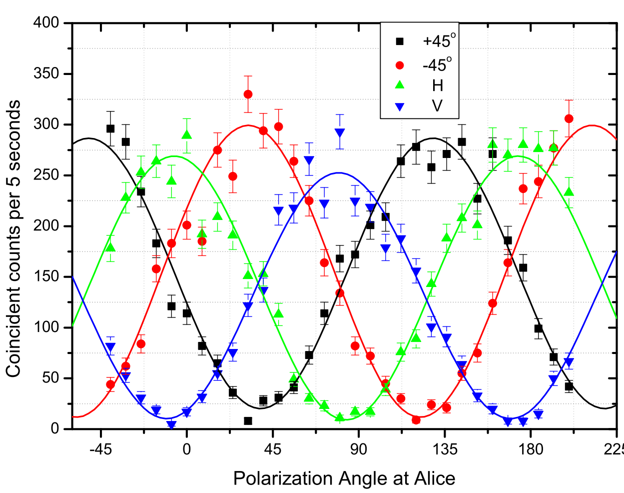

FIG. 3: Verification of the distributed quantum entanglement. In order to test the quality of the entangled state between the two receivers, we measured the coincident count as a function of Alice's polarization angle. Four curves correspond to four polarization angles (H,V,+45, -45) set at Bob. The data is best fitted with sin functions, showing that the visibility is 94% in H/V basis and it is 89% in +45/-45 basis. The average visibility has reached 91%, which is far beyond the threshold required for a violation of Bell inequality.

TABLE I: Measured correlation coefficients required for CHSH inequality

$E(\phi_A,\phi_B)$	$(0°,22.5°)$	$(0°,67.5°)$	$(45°,22.5°)$	$(45°,67.5°)$
Value	-0.681	0.764	-0.421	-0.581
Deviation	0.040	0.036	0.052	0.046

where photon A is sent to Alice, photon B is sent to Bob, H and V represent horizontal and vertical polarization. The local visibility at the Sender is about 98% in the H/V basis, and 94% in the +45/-45 basis. The observed visibilities between two separated receivers are 94% and 89% in the H/V and +45/-45 bases, respectively (see Fig.3). Hence the average visibility reaches 91%, which is well beyond 71% required for a violation of Bell inequality. In order to further test the quality of the entangled state, we measured the Clauser-Horne-Shimony-Holt (CHSH) inequality which is one type of Bell inequalities [17]. The polarization correlation coefficient is defined as follows,

$$E(\phi_A,\phi_B)=\frac{N_{++}+N_{--}-N_{+-}-N_{-+}}{N_{++}+N_{--}+N_{+-}+N_{-+}} \tag{2}$$

Where $N_{ij}(\phi_A,\phi_B)$ are the coincidences between the i channel of the polarizer of Alice set at angle ϕ_A and the j channel of the polarizer of Bob set at angle ϕ_B. In the CHSH inequality, parameter S is defined as,

$$S=|E(\phi_A,\phi_B)-E(\phi_A,\phi'_B)+E(\phi'_A,\phi_B)+E(\phi'_A,\phi'_B)| \tag{3}$$

In the local realistic view, no matter what angles ϕ_A and ϕ_A are set to, parameter S should be below 2. But in the view of quantum mechanics, S will get to the maximal value $2\sqrt{2}$ when the polarization angles are set to $(\phi_A,\phi'_A,\phi_B,\phi'_B)=(0°,45°,22.5°,67.5°)$

As the detection loophole existed in all previous photonic test of local realism [18, 19, 20], here we are only going to show a violation of Bell inequality with space-like separated observers. To do so, at each observer a beamsplitter (see Fig.2) is used to achieve the true random basis selection and use 4 single photon detectors to perform the $(0°,45°,22.5°,67.5°)$ polarization measurement. With emphasis, we note that our passive beamsplitter is sufficient to provide a bona fide test of the locality loophole. This is because in experiments using low efficient detectors the locality loophole can be closed equivalently using active or passive switches [21]. In our experiment, the whole measurement progress was completed in 20 seconds. Note that, all the 16 coincident counts are measured simultaneously with two receivers space-like separated. Moreover, since different detectors have different detection efficiency two-fold coincidence normalization has been performed based on the single count rate. The measured result of parameter S is 2.45 ± 0.09, with a violation of the CHSH inequality by 5 standard deviations (see Table I for details). This re-

sult firmly ascertains that entanglement has been built between the two distant receivers.

In the cryptography experiment, we take a variant scheme of BB84 with entangled photons [1]. In this scheme, with the help of the beamsplitter Alice and Bob randomly measure her/his received photons in the H/V or +45/-45 basis. Because of the perpendicular property in polarization of $|\psi^-\rangle$, when they have chosen the same basis, their private keys are anti-correlated. Then identical keys can be easily got, if one of them converts all her/his keys. In 4 minutes, we obtained 29,433 coincidence events. Due to the difference of the collecting efficiency of the four couplers at each receiver, we have randomly discarded some events related to the high-efficiency couplers in order to make the efficiency of the couplers at each receiver equal, and after this progress, we got 15,308 coincidence events. Discarding the events that Alice and Bob had chosen different bases, we got 7,956 bits of sifted key, and the QBER is 5.83%. Then we did error correction, and decreased the key size to 4,869 bits with an error rate of 1.46%. After the privacy amplification procedure depending on the QBER, finally we got 2435 bits of final secure key. This corresponds an average key distribution rate of 10bit/second. Note that, using a recent high-intensity entangled photon source [22] one can easily increase the average key distribution rate to a few hundreds per second.

Although compared to the previous experiments our experimental results might seem to be only a modest step forward, the implication is profound. First, our experiment demonstrated for the first time the entanglement can still survive after penetrating the effective thickness of the aerosphere by showing a violation of Bell inequality with space-like separated observers. Obviously, the strong violation of Bell inequality is sufficient to guarantee the absolute security of the quantum cryptography scheme, hence closing the eavesdropping loophole. Second, the link efficiency of entangled photon pairs achieved in our experiment is about a few percent, which is well beyond the threshold required for satellite-based free-space quantum communication [13]. Finally, the methods developed in the present experiment to establish a high stable transmission channel and achieve synchronization between two distant receivers provide the necessary technology for future experimental investigations of global quantum cryptography and quantum teleportation in free-space.

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[1] C. H. Bennett and G. Brassard, in Proc. IEEE Int. Conf. on Computers, Systems and Signal Processing 175 (IEEE, New York, 1984).
[2] A. Ekert, Phys. Rev. Lett. **67**, 661 (1991).
[3] C. H. Bennett et al., Phys. Rev. Lett. **70**, 1895 (1993).
[4] N. Gisin, G. Ribordy, W. Tittel and H. Zbinden, Rev. Mod. Phys. **74**, 145 (2002).
[5] H.-J. Briegel et al., Phys. Rev. Lett. **81**, 5932 (1998).
[6] M. Zukowski, A. Zeilinger, A., M. A. Horne and A. K. Ekert, Phys. Rev. Lett. **71**, 4287 (1993).
[7] C. H. Bennett et al., Phys. Rev. Lett. **76**, 722-725 (1996).
[8] J.-W. Pan, D. Bouwmeester, H. Weinfurter and A. Zeilinger, Phys. Rev. Lett. **80**, 3891 (1998).
[9] J.-W. Pan et al., Nature **423**, 417 (2003).
[10] A. Kuzmich et al., Nature **423**, 731 (2003).
[11] C. H. Van der Wal et al., Science **301**, 196 (2003).
[12] D. N. Matsukevich and A. Kuzmich, Science **306**, 663 (2004).
[13] M. Aspelmayer et al., IEEE journal of Selected Topics in Quantum Electronics, Vol. **9**, Issue 6, 1541 (2003).
[14] C. Kurtsiefer et al., Nature **419**, 450 (2002).
[15] M. Aspelmayer et al., Science **301**, 621 (2003).
[16] P. G. Kwiat et al., Phys. Rev. Lett. **75**, 4337 (1995).
[17] J. Clauser, M. Horne, S. Shimony, and R. Holt. Phys. Rev. Lett. **23**, 880 (1969).
[18] A. Aspect, J. Dailibard and G. Roger, Phys. Rev. Lett. **49**, 1984 (1982).
[19] G. Weihs et al., Phys. Rev. Lett. **81**, 5039 (1998).
[20] W. Tittel, J. Brendel, H. Zbinden and N. Gisin, Phys. Rev. Lett. **81**, 3563 (1998).
[21] N. Gisin and H. Zbinden, Phys. Lett. A **264**, 103 (1999).
[22] C. Kurtsiefer, M. Oberparleiter and H. Weinfuter, Phys. Rev. A, **64**, 023802 (2001).